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Major Building Materials in Terms of Environmental Impact Evaluation of School Buildings in South Korea

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Abstract: This study aimed to analyze the major building materials in terms of environmental impact evaluation of school buildings in South Korea. Three existing school buildings were selected as the analysis targets, and building materials were analyzed in terms of cumulative weight and six environmental impact categories (global warming potential, abiotic depletion potential, acidification potential, eutrophication potential, ozone-layer depletion potential, and photochemical oxidation potential). The materials were analyzed from an environmental perspective after integrating the six environmental impact categories into the environmental costs. From the analysis, nine major building materials, including ready-mixed concrete, concrete bricks, aggregate, rebar, cement, stone, glass, insulating materials, and wood, were selected for the school buildings. These analysis results can be used as a streamlined evaluation of the environmental impacts of school buildings. It is thought that the simplified life cycle assessment will help make decisions considering environmental characteristics in the early stage of the construction project. Additionally, it will be possible to make LCA efficient in terms of time and cost, one of the largest constraints of the existing building LCA, and effective reduction in the environmental load.

Keywords: school building; major building material; environmental impact; streamlined evaluation; life cycle assessment

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1. Introduction

Recently, environmental problems such as global warming, air pollution, and ozone depletion have increased globally. The 26th climate-change convention conference was held in November 2021 in Glasgow, UK, and the rules required for implementing the Paris agreement, a climate regime agreement adopted in 2015, were discussed. In response to such international movements, the South Korean government has recently raised the target for the reduction of greenhouse gas emissions compared to the business-as-usual (BAU) levels to 40% by 2030, as opposed to its initial target of reduction by 37% announced in 2018. To this end, it is implementing various policies, including the green-building support law and green-building basic plan, to reduce the greenhouse-gas emissions of the construction sector, which account for a quarter of the national greenhouse gas emissions.

In particular, Life Cycle Assessments (LCAs) research that quantitatively evaluates and analyzes information on the environmental load that occurs during the life cycle of a building is actively underway. Environmentally advanced countries have adopted their own Green building certification systems (LEED, BREEAM, etc.) to reduce the greenhouse gases emitted from the buildings and established Life Cycle Assessment Certification items for building to gradually improve the qualification standard [1]. In Korea, the green building certification system(G-SEED) was improved in 2016 to evaluate and analyze information on the environmental load that occurs during the life cycle of a building and induces the establishment of a plan to reduce by stages the six major environmental impacts, including greenhouse gas.

The environmental load generated from buildings must consider not only the energy consumption that occurs from the operation stage of buildings but also the environmental impacts of the building materials used during their construction process [2]. This is because the environmental impacts of the production, construction, and disposal stages of building materials account for approximately 40% of the environmental pollution in terms of the building life cycle. However, as buildings are composed of numerous building materials, assessing the environmental impacts of building materials is time-consuming and costly [3]. In particular, the building production-stage assessment at the design stage, in which the environmental-load reduction is the most effective, has been acting as the largest constraint element for the application of life-cycle assessment (LCA) owing to frequent design changes [4] and the fact that the types and quantities of all the building materials used for a building must be identified using limited information only [5,6]. As such, an LCA method is required that is based on major building materials representing environmental impacts; accordingly, many related studies have been conducted locally and internationally because the environmental load can be effectively reduced, and the LCA of buildings can be efficiently performed simply by deriving major building materials with high environmental impact [7–9]. However, related studies have so far focused on apartment buildings, and they have limited their analysis scope only to the global warming index, which represents CO_2 emissions, among various environmental impact categories [10]. In addition, as domestic studies have applied the inter-industry analysis database, in which CO_2 emissions are estimated based on the product cost, the accuracy of the obtained results has been somewhat insufficient. In particular, in the case of school buildings, it is necessary to collect characteristics of buildings to investigate the causes of uncertainty since they are highly influenced by social and environmental factors and to predict risk and environmental characteristics through simplified evaluation methods [11,12]. Although school buildings have the most green-building certifications in South Korea after residential buildings, studies on LCA and descriptions considering the characteristics of school buildings by type are significantly insufficient. It is very difficult to predict environmental emissions as decision-making in the early design phase of the construction project is made under uncertainty. In particular, it is necessary to select major building materials used in school buildings for efficient life cycle assessment in terms of time and cost, which is one of the biggest constraints on the existing building life cycle assessment, and effective environmental load reduction must be made based on the main building materials.

This study aimed to analyze the major building materials in terms of environmental impact evaluation of school buildings as part of the study on the LCA. For this purpose, three existing school buildings were selected as the analysis target. Weight-based major building materials, with high cumulative weight contribution, among building materials used for building construction were analyzed based on the bills of quantities of the schools. Furthermore, the major building materials were analyzed concerning six environmental impact categories and integrated environmental aspects based on environmental cost, and those of school buildings were analyzed considering both the weight and environmental aspects.

2. Literature review

2.1. Life Cycle Assessment

LCA quantitatively assesses potential environmental impacts that may arise from inputs and outputs throughout the life cycle, including the production, construction, operation, and disposal of building materials [13–18]. According to ISO 14040s, LCA consists of four stages: goal and scope definition, life-cycle inventory (LCI) analysis, life-cycle impact assessment, and life-cycle interpretation (ISO/FDIS 14040, 2006). Figure 1 shows the structure of LCA according to ISO 14040s. Figure 1 shows the composition of LCA.

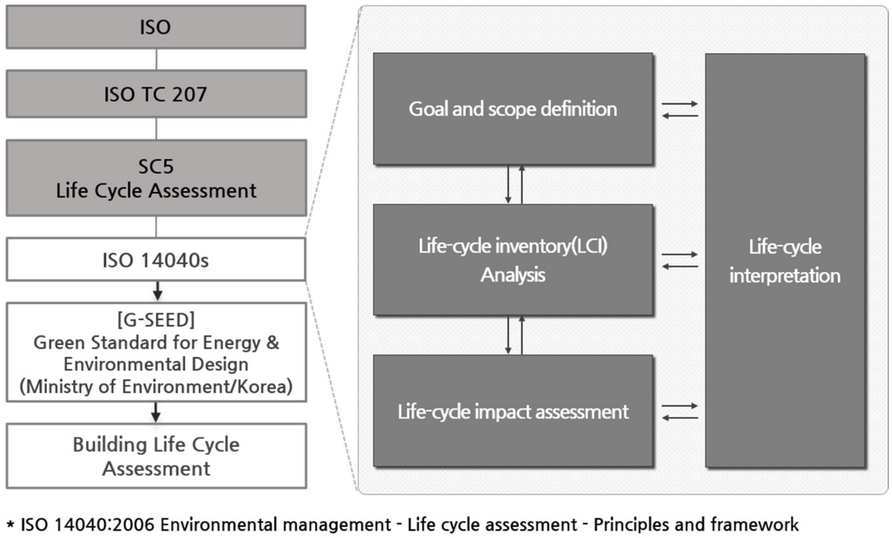


Figure 1. Composition of LCA.

Goal and scope definition, the first stage of LCA, is a basic stage required to set the research purpose and determine where the results will be applied. The research scope includes the system boundary, function unit, impact assessment method, data requirements, and the assumptions and constraints of the research (ISO/DIS 14041, 2006). Based on the system set in the goal and scope definition stage, the types and quantities of all raw materials and energy inputs to the system and all the files, by-products, and environmental pollutants emitted from the system are recorded and listed in the LCI analysis stage. This stage primarily aims to assemble the input and output data of each stage. Life cycle impact assessment is essential for identifying the environmental portion in performing LCA. The purpose of this stage is to quantitatively and qualitatively estimate the extent of environmental impacts by connecting certain environmental loads with an inventory database based on the inventory analysis. According to ISO 14040s, the life-cycle impact assessment is divided into classification, characterization, normalization, and weighting stages. Life-cycle interpretation, which is the last component of LCA, analyzes the results of LCI analysis or life-cycle impact assessment. Based on the analysis results, the major environmental issues of the system are identified.

2.2. Research Trends

Table 1 shows the published studies related to building LCA. A. Sharma, M.M Khasreen, Haibo, and Yashwanth emphasized the importance of LCA while proposing the basic concept, management measures, and methodologies of building LCA [19–22]. They suggested the necessity of system maintenance related to eco-friendly buildings and the basic matters for introducing the system, such as introducing the building environmental performance certification system by the LCA and incentives for eco-friendly buildings to foster sustainable buildings. Verbeeck and Hens [23], Bribián et al. [24], and Dascalaki et al. [25] emphasized the importance of LCI databases (DBs) for LCA and conducted studies on LCI DB construction. Further, the basic units of the intrinsic energy consumption of major building materials and carbon dioxide emission that can be used as a judgment tool for selecting alternatives that can reduce the environmental impact of buildings were established [23–25]. Roh et al. [26], Gardner et al. [27], and Li [28] conducted studies to assess the environmental load for certain stages and to comprehensively analyze CO_2 emitted throughout the life cycle. In addition, a method of predicting the emission of environmental load generated from buildings was presented using only simple LCA analysis to improve the time-consuming and labor-intensive disadvantages of the existing LCA analysis of buildings [26–28]. Roh et al. [29] and Pamu et al. [30] conducted a study that can efficiently evaluate comprehensive building activities according to an evaluation of construction projects. The comparison and analysis of the staged emission characteristics of buildings are ongoing such as the development of the software program for assessing CO_2 emission during the building life-cycle for designing buildings with reduced carbon emissions [4,30–34]. Although various studies on LCA have been conducted, most of them are limited to apartment buildings.

Table 1. Research related to LCA.

Classification	Researchers	Research Contents
Basic concept and Methodology	Khasreen et al. (2009)	Life-Cycle Assessment and the Environmental Impact of Building
	Sharma et al. (2011)	Life cycle assessment of buildings: A review
	Haibo et al. (2022)	Uncertainties in whole-building life cycle assessment: A systematic review
Database construction of CO_2 emission per unit	Yashwanth et al. (2022)	Life Cycle Assessment of a building using Open-LCA software
	Verbeeck & Hens (2009)	Life cycle inventory of buildings: A contribution analysis
	Bribián et al. (2010)	Life cycle assessment of building materials: Comparative analysis of energy and environmental impacts and evaluation of the eco-efficiency improvement potential
Environmental impact assessment	Dascalaki et al. (2021)	Analysis of the embodied energy of construction materials in the life cycle assessment of Hellenic residential buildings
	Roh et al. (2018)	Analysis of Embodied Environmental Impacts of Korean Apartment Buildings Considering Major Building Materials
	Gardner et al. (2019)	Materials life cycle assessment of a living building
	Li (2021)	Integrating climate change impact in new building design process: A review of building life cycle carbon emission assessment methodologies
Development of LCA program	Roh et al. (2016)	Development of a building life cycle carbon emissions assessment program (BEGAS 2.0) for Korea’s green building index certification system
	Pamu et al. (2021)	Life Cycle Assessment of a building using Open-LCA software
School Building of LCA in South Korea	Tae et al. (2010)	A Study on Realization Method of Low Carbon School Building
	Ji et al. (2016)	Evaluation of life cycle energy consumption and CO_2 emission of Elementary School of Buildings

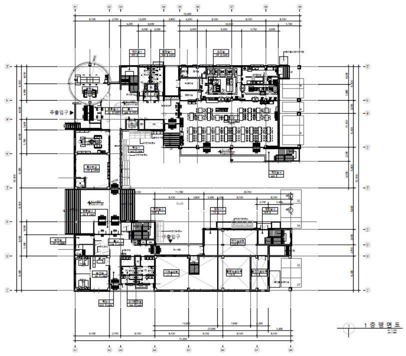
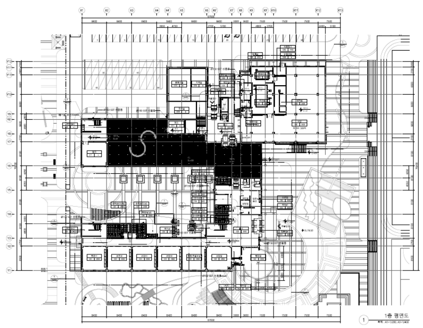
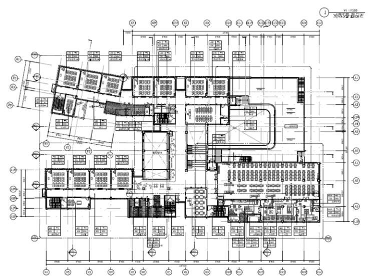
Studies related to LCA of school buildings in South Korea include one study on a method for realizing low carbon school buildings and another on assessing the life-cycle energy consumption and CO_2 emissions for school buildings, among others [35,36]. However, the assessment methods and technologies for performing LCA for school buildings, which have the most environment-friendly certifications after apartment buildings, are significantly insufficient compared to those for apartment buildings, and most of them are limited to energy consumption. Thus, research that considers the life cycle of school buildings, which correspond to public facilities, is required.

3. Materials and Methods

3.1. Analysis Target

To analyze the major building materials of school buildings, three school buildings constructed in the reinforced concrete (RC) structure in South Korea were selected as the analysis targets, as shown in Table 2. Among them, Case A and B were an elementary school and a high school, respectively, both located in Gyeonggi-do. Case C was an elementary school located in Seoul.

Table 2. Overview of the analysis targets.

Division	**Case A**	
Location	Gyeonggi	
Structure	RC structure	
Total floor area	6950.00 m^2	
Size	5 Floor	
Building Area	1992.36 m^2	
Application	School building	
Division	**Case B**	
Location	Gyeonggi	
Structure	RC structure	
Total floor area	10,186.19 m^2	
Size	4 Floor	
Building Area	3325.3 m^2	
Application	School building	
Division	**Case C**	
Location	Seoul	
Structure	RC structure	
Total floor area	11,634.23 m^2	
Size	5 Floor	
Building Area	3346.26 m^2	
Application	School building	

3.2. Analysis Method

Figure 2 shows the proposed analysis method. In this study, major building materials required as database input in the production, construction, and disposal stages, which account for 40% of the environmental impacts occurring in the whole life cycle, were analyzed. It is possible to simplify the environmental impact assessment of buildings on the environmental impacts of production, construction, and disposal by selecting major building materials. First, weight-based building materials were analyzed to find the major building materials among building materials used in the construction of school buildings. In addition, major building materials were analyzed from an environmental perspective to identify materials with high environmental loads even though they can be excluded by the weight-based method. First, major building materials were analyzed for six environmental impact categories: global warming potential (GWP), abiotic depletion potential (ADP), acidification potential (AP), eutrophication potential (EP), ozone layer depletion potential (ODP), and photochemical oxidation potential (POCP). Then, the materials were analyzed from an environmental perspective after integrating the six environmental impact categories into the KOLID environmental cost. Through the analyzed results, major building materials were identified for school buildings in terms of weight and environment.

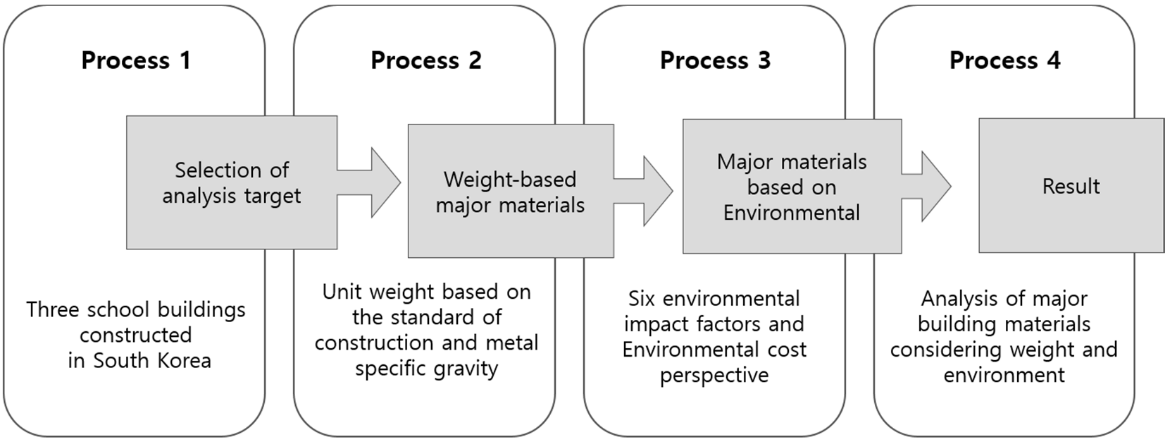


Figure 2. Analysis procedure of major building materials.

3.2.1. Weight-Based Analysis Method

The weight-based analysis method is the most basic cut-off criteria analysis method specified by ISO 14040s: the international standard for LCA. The cut-off criteria refer to the data collection criteria set during the LCA input investigation process of LCA to improve the ease of the LCA process, and 95% or 99% of the total weight is mostly set. In this study, the cut-off criterion was set at 95%.

The construction range was categorized using the design documents and bills of quantities of the three selected school buildings. The input quantities of building materials for construction were investigated according to the scope of the G-SEED evaluation. Such amounts were converted into the weight unit, and the major building materials that corresponded to over 95% of the total weight were analyzed. The unit weight criteria of building materials refer to the construction standard estimates, construction specifications, and metal-specific gravity table in South Korea, as shown in Table 3. Temporary materials (e.g., formwork, floor post, and safety materials) that are recovered after use in the building construction stage and reused at other construction sites were excluded from the system boundary of this study. Furthermore, uncommon materials and attached hardware materials used for school buildings were excluded from the analysis scope.

Table 3. Unit weight with respect to building material (partial).

Materials	Unit Weight	Unit	Source
Reinforced Concrete	2400	kg/m^3	Standard of Construction Estimates
Plain Concrete	2300	kg/m^3	Standard of Construction Estimates
Cement Mortar	2100	kg/m^3	Standard of Construction Estimates
Cement	40	kg/Bag	Standard of Construction Estimates
Sand	1600	kg/m^3	Standard of Construction Estimates
Gravel	1700	kg/m^3	Standard of Construction Estimates
Granite	2650	kg/m^3	Standard of Construction Estimates
Marble	2700	kg/m^3	Standard of Construction Estimates
Glass	2520	kg/m^3	Standard of Construction Estimates
Stainless Steel (STS340)	7930	kg/m^3	Standard of Construction Estimates
Stainless Steel (STS430)	7700	kg/m^3	Standard of Construction Estimates
Aluminum	2700	kg/m^3	Metal Specific Gravities Table

3.2.2. Environmental Impact-Based Analysis Method

Analysis based on environmental impact categories is a step to identify major building materials that can be excluded by the weight-based analysis method even though their environmental impacts are significant.

In this study, the six categories, GWP, AP, ADP, EP, ODP, and POCP, identified by ISO 14025 as the major environmental impact categories, were considered, and the major building materials corresponding to the exclusion criterion of 95% for each environmental impact category were selected. In addition, to convert the six environmental-impact categories into a single unit, they were integrated into the KOLID environmental cost, a Korean damage estimation type and the major building materials were analyzed in terms of the environmental cost [37]. In this instance, the national LCI DB, developed by the Korea Ministry of Environment and the Ministry of Trade, Industry and Energy, and the building material environmental information national DB constructed by the Korea Ministry of Land, Infrastructure and Transport were used for the environmental impact characterization values of building materials. Table 4 illustrates the six environmental impact characterization values of building materials.

Table 4. Six environmental impact DB concerning building materials(partial).

Building Material	Unit	Six Environmental-Impact Characterization Values of Building Materials					
		GWP	ADP	AP	EP	ODP	POCP
		kg-CO_2eq/Unit	kg-Sbeq/Unit	kg-CFC-11eq/Unit	kg-SO_2eq/Unit	kg-PO43-eq/Unit	kg-C_2H_4eq/Unit
Unsaturated polyesters	L	2.87×10^{0}	3.62×10^{-2}	7.14×10^{-3}	6.56×10^{-4}	9.35×10^{-7}	2.48×10^{-3}
Water soluble emulsion	L	3.23×10^{-1}	6.49×10^{-3}	1.13×10^{-3}	9.53×10^{-5}	8.51×10^{-8}	4.05×10^{-4}
Water soluble liquid	L	1.19×10^{0}	1.48×10^{-2}	7.62×10^{-3}	9.99×10^{-4}	2.71×10^{-8}	4.04×10^{-4}
Aminoalkyd paint	L	8.37×10^{-1}	1.80×10^{-2}	3.77×10^{-3}	1.83×10^{-3}	4.06×10^{-8}	3.65×10^{-4}
Alkyd−enamel	L	2.26×10^{-1}	2.42×10^{-2}	1.63×10^{-3}	1.18×10^{-4}	2.03×10^{-8}	1.82×10^{-4}
Urethane paint	L	3.89×10^{2}	4.59×10^{0}	1.05×10^{0}	1.04×10^{-1}	1.40×10^{-4}	4.17×10^{-1}

4. Results

4.1. Weight-Based Analysis of the Major Building Materials

Table 5 lists the results of the weight-based analysis of major building materials. According to the table, as the major building materials corresponding to the cut-off criteria of 99%, ready-mixed concrete, concrete bricks, aggregate, rebar, and cement were selected for school building A, and ready-mixed concrete, aggregate, concrete bricks, rebar, and cement were selected for school building B. In addition, ready-mixed concrete, aggregate, concrete bricks, rebar, and stone were selected as the major building materials for school building C. The major building materials for school building C corresponded to an exclusion criterion of 95%. A comparison of the major building materials for school buildings A, B, and C confirmed that similar building materials such as ready-mixed concrete, concrete bricks, aggregate, rebar, cement, stone, and glass were selected as major building materials for school buildings judging only from the types of building materials, even though the weight proportions or ranks of the major building materials varied depending on the size or total floor area of schools.

Table 5. Major building materials by weight ratio.

Rank	Case A			Case B			Case C		
	Materials	Ratio (%)	Cumulative (%)	Materials	Ratio (%)	Cumulative (%)	Materials	Ratio (%)	Cumulative (%)
1	Ready-mixed Concrete	67.5	67.50	Ready-mixed Concrete	71.05	71.05	Ready-mixed Concrete	73.29	73.29
2	Concrete Brick	12.11	79.61	Aggregate	10.12	81.17	Aggregate	9.74	83.03
3	Aggregate	9.82	89.43	Concrete Brick	9.78	90.94	Concrete Brick	8.35	91.38
4	Rebar	3.11	92.54	Rebar	3.39	94.33	Rebar	3.65	95.03
5	Cement	3.03	95.57	Cement	2.73	97.06	Stone	1.69	96.72
6	Stone	2.04	97.61	Stone	1.51	98.58	Cement	1.67	98.39
7	Glass	1.17	98.78	Glass	0.37	98.94	Glass	0.77	99.16
8	Iron Frame	0.35	99.13	Tile	0.28	99.22	Tile	0.21	99.37
9	Tile	0.28	99.41	Iron Frame	0.24	99.46	Insulating Materials	0.19	99.56
10	Gypsum	0.14	99.55	Wood	0.14	99.60	Gypsum	0.15	99.71
11	Wood	0.13	99.69	Gypsum	0.11	99.71	Iron Frame	0.14	99.85
12	Insulating Materials	0.13	99.82	Insulating Materials	0.10	99.81	Wood	0.10	99.95
13	Metal	0.08	99.90	Metal	0.10	99.91	Paint	0.02	99.97
14	Etc.	0.16	100	Etc.	0.1	100	Etc.	0.03	100
Total		100			100			100	

In addition, as a result of analyzing the major building materials corresponding to the exclusion criterion of 95%, ready-mixed concrete, concrete bricks, aggregate, rebar, and cement were identified as the weight-based major building materials, even though the building material proportions differed depending on the schools. For all schools, the average weight ratio was approximately 70.61% for ready-mixed concrete, 10.08% for concrete bricks, 9.98% for aggregate, 3.38% for rebar, and 2.48% for cement. These materials met the exclusion criterion of 95%. Other materials based on the exclusion criterion of 99% were stone (1.75%), glass (0.77%), tiles (0.25%), iron frame (0.24%), gypsum (0.14%), wood (0.12), and insulating materials (0.13%).

Therefore, in this study, the five building materials that met the exclusion criterion of 95%, including ready-mixed concrete with the highest weight ratio, were selected as the weight-based major building materials for school buildings. It appears that different analyses will be possible depending on the use of buildings.

4.2. Environmental Impact-Based Analysis of the Major Building Materials

To analyze building materials with significant environmental impacts, which can be excluded by the weight-based assessment method, major building materials were assessed considering the characterization value of each of the six environmental impact categories (GWP, ADP, AP, EP, ODP, and POCP) based on the quantities calculated above. As a result of analyzing major building materials based on the six environmental impact categories, each category exhibited somewhat different major building materials based on the exclusion criterion of 95% because of the different characterization values of the environmental impact categories. Table 6 lists the environmental impact emission ratios for EP and ADP among the six environmental impacts. Eutrophication causes rapid growth of aquatic plants due to excessive supply of organic matter and nutrients to rivers and lakes and causes green tide and red tide. Substances that cause eutrophication do not occur directly in the production process of buildings but occur indirectly in the production process of building materials. Abiotic Depletion Potential refers to the environmental impact caused by consuming the Earth's resources. As construction waste accounts for about 50% of waste, the impact of Abiotic Depletion Potential is a very important factor in the construction industry. Therefore, it is necessary to analyze building materials that have a high environmental impact in addition to the major building materials based on weight. The analysis of the major building materials for EP showed that wood, which was not included in the weight-based major building materials, was included with high ratios of 16.05%, 21.17%, and 16.32% for each case based on the exclusion criterion of 95%. In the case of ADP, insulating materials were included with high ratios of 27.26%, 21.91%, and 36.32% for each case based on the exclusion criterion of 95%.

Table 6. Analysis of major building materials for EP and ADP.

Rank	Eutrophication Potential(EP)						Acidification Potential (ADP)					
	Case A		Case B		Case C		Case A		Case B		Case C	
	Materials	Ratio (%)	Materials	Ratio (%)	Materials	Ratio (%)	Materials	Ratio (%)	Materials	Ratio (%)	Materials	Ratio (%)
1	Stone	30.04	Ready-mixed Concrete	33.40	Ready-mixed Concrete	36.47	Ready-mixed Concrete	38.96	Ready-mixed Concrete	45.77	Ready-mixed Concrete	40.69
2	Ready mixed Concrete	25.99	Wood	21.17	Rebar	17.73	Insulating Materials	26.72	Insulating Materials	21.91	Insulating Materials	36.32
3	Wood	16.05	Rebar	15.57	Wood	16.32	Rebar	10.00	Rebar	12.12	Rebar	11.39
4	Rebar	11.70	Stone	13.44	Stone	13.08	Glass	7.41	Metal	5.17	Stone	3.33
5	Cement	6.09	Cement	6.71	Insulating Materials	7.16	Metal	4.02	Cement	3.96	Glass	2.67
6	Insulating Materials	3.96	Insulating Materials	3.57	Cement	4.33	Cement	3.95	Stone	3.32	Cement	2.11
7	Stone	2.97	Concrete Brick	2.93	Concrete Brick	2.65	Stone	3.30	Concrete Brick	1.83	Concrete Brick	1.37
8	Glass	0.73	Metal	0.90	Glass	0.81	Concrete Brick	2.04	Glass	1.66	windows	0.62
9	Etc	2.48	Etc	2.31	Etc	1.44	Etc	3.60	Etc	4.26	Etc	1.5
Total		100		100		100		100		100		100

Figure 3 shows the major building materials in the six environmental impact categories for cases A, B, and C. For GWP, the major building materials were ready-mixed concrete, concrete bricks, cement, aggregate, rebar, stone, and glass. Ready-mixed concrete, insulating materials, rebar, glass, metals, cement, concrete bricks, and stone were found to be the major building materials for ADP. For AP, the major building materials were ready-mixed concrete, rebar, insulating materials, cement, stone, concrete bricks, and wood. For EP, they were ready-mixed concrete, cement, concrete bricks, rebar, stone, and glass based on the exclusion criterion of 95%. Ready-mixed concrete, cement, concrete bricks, rebar, and glass were analyzed to be the major building materials for ODP, while ready-mixed concrete, glass, rebar, cement, and insulating materials were found to be the major building materials for POCP.

In particular, for Case A, the rank of glass for ODP was higher compared to those of other buildings. This is because a higher amount of tempered glass was used in Case A compared with those of Cases B and C according to a review of the bills of quantities as well as environmental impact assessment. This confirms that the characteristics of building materials, as well as the environmental characterization value of each environmental impact category, affect the environmental impact index. Considering this, if environment-friendly building materials are selected in the design stage, they are expected to effectively reduce the environmental load in terms of LCA.

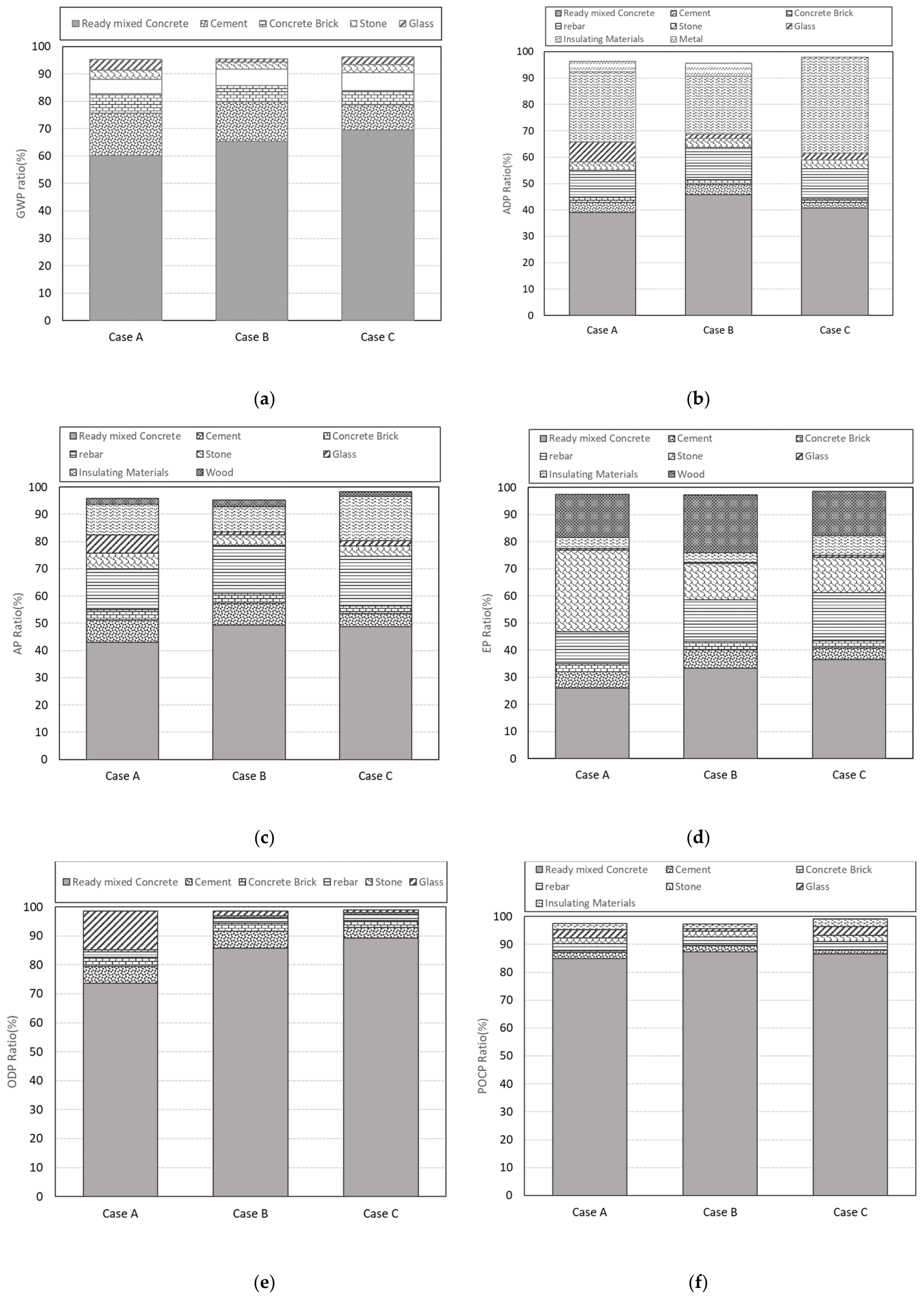


Figure 3. Major materials by six environmental impact categories. (**a**) Cumulative global warming(GWP) of major building materials. (**b**) Cumulative Abiotic Depletion Potential (ADP) of major building materials. (**c**) Cumulative acidification(AP) of major building materials. (**d**) Cumulative eutrophication(EP) of major building materials. (**e**) Cumulative ozone depletion(ODP) of major building materials. (**f**) Cumulative photochemical oxidant creation(POCP) of major building materials.

In addition, to convert the above six environmental impact categories into a single unit, the selected building materials were integrated into the KOLID environmental cost and analyzed in terms of the environmental cost. The KOLID environmental cost is a damage-estimation-type life cycle impact assessment method capable of integrating the life cycle impact assessment results into a monetary value [37]. Table 7 lists the major material analysis results in terms of environmental cost for Cases A, B, and C. According to the results, the contribution rate of each ready-mixed concrete to the environmental aspect of each case was analyzed, the highest being 44.72%, 51.21%, and 50.97%. Contrary to the weight basis, it was analyzed that the contribution rate of insulation and stone materials to the environment was high. Figure 4 shows the major building materials in terms of environmental cost. As shown in Figure 4, the major building materials from an environmental perspective based on the exclusion criterion of 95% are ready-mixed concrete (48.97%), rebar (15.81%), insulating materials (11.02%), cement (7.00%), stone (4.76%), concrete bricks (3.38%), glass (3.14%), and wood (2.58%). These major building materials include ready-mixed concrete, rebar, cement, and concrete bricks, weight-based major building materials, and another four materials (insulating materials, stone, glass, and wood).

Table 7. Major material analysis results in terms of the environmental cost.

Rank	Case A			Case B			Case C		
	Materials	**Ratio (%)**	**Cumulative (%)**	**Materials**	**Ratio (%)**	**Cumulative (%)**	**Materials**	**Ratio (%)**	**Cumulative (%)**
1	Ready-mixed Concrete	44.72	44.72	Ready-mixed Concrete	51.21	51.21	Ready-mixed Concrete	50.97	50.97
2	Rebar	13.88	58.60	Rebar	16.46	67.67	Rebar	17.08	68.04
3	Insulating Materials	10.10	68.71	Insulating Materials	8.11	75.78	Insulating Materials	14.84	82.88
4	Cement	8.20	76.91	Cement	8.06	83.84	Cement	4.74	87.62
5	Stone	6.40	83.31	Stone	3.90	87.74	Stone	3.96	91.58
6	Glass	6.21	89.52	Concrete Brick	3.43	91.17	Concrete Brick	2.82	94.40
7	Concrete Brick	3.90	93.42	Wood	3.04	94.20	Wood	2.13	96.54
8	Wood	2.58	96.01	Metal	2.14	96.34	Glass	1.93	98.46
9	Metal	1.70	97.70	Glass	1.27	97.61	Tile	0.38	98.84
10	Window framing	0.58	98.29	Tile	0.52	98.14	Window framing	0.29	99.13
11	Etc	1.71	100.00	Etc	1.86	100.00	Etc	0.87	100.00
Total		100.00	100.00		100.00	100.00		100.00	100.00

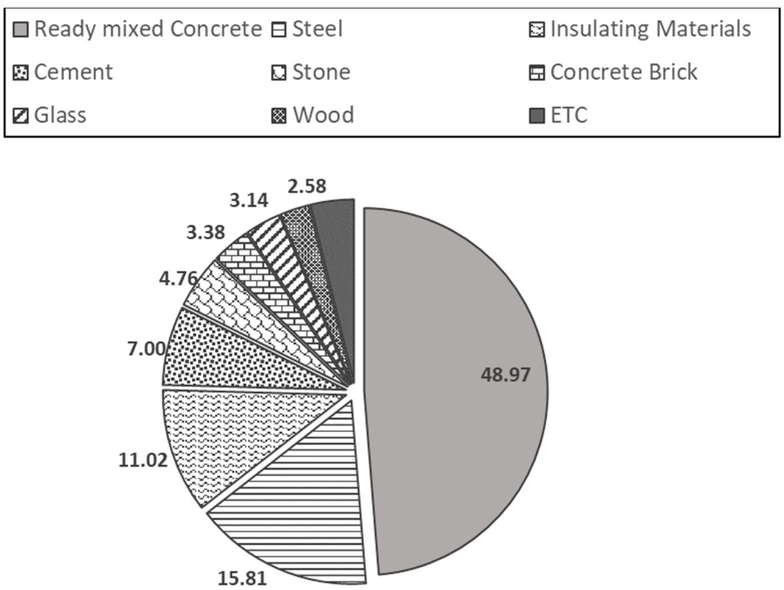


Figure 4. Major building materials in terms of environmental cost.

5. Discussion

Table 8 lists the nine major building materials, which were comprehensively analyzed based on the weight-based major building materials and the major building materials from an environmental perspective. The weight-based major building materials were ready mixed concrete, concrete bricks, aggregate, rebar, and cement-based on the exclusion criterion of 95%. In addition, the major building materials from an environmental perspective included ready-mixed concrete, concrete bricks, rebar, and cement, which were also weight-based major building materials, as well as insulating materials such as stone, glass, and wood, which are significantly influential from an environmental perspective and must be considered for school building LCA even though they were excluded by the weight-based assessment method. In the case of ready mixed concrete, the amount of input to the building is high, and It was analyzed that the environmental impact was also the highest because the amount of cement added to the concrete was high. In the case of insulation, stone, glass, and wood, they showed a low contribution in terms of weight, but analysis showed them to contribute highly to environmental aspects such as global warming, abiotic depletion, and eutrophication.

Table 8. Major building materials considering weight and environment.

Basis of Weight		Environmental Aspects			Major Building Materials
Materials	Ratio (%)	Materials	Ratio (%)		
Ready-mixed Concrete	70.61	Ready-mixed Concrete	48.97		Ready-mixed Concrete
Concrete Brick	10.08	Steel	15.81		Concrete Brick
Aggregate	9.89	Insulating Materials	11.02		Aggregate
Steel	3.38	Cement	7.00		Steel
Cement	2.48	Stone	4.76	→	Cement
Stone	1.75	Concrete Brick	3.38		Insulating Materials
Glass	0.77	Glass	3.14		Stone
Tile	0.25	Wood	2.58		Glass
Iron Frame	0.24	Metal	1.92		Wood
Insulating Materials	0.14	Tile	0.46		
Etc	0.45	Etc	1.46		
	100		100		

If environmental product declarations (EPD) and low carbon products are applied to the nine major building materials, which are ready-mixed concrete, concrete bricks, aggregate, rebar, cement, stone, glass, insulating materials, and wood when designing school buildings, it will be possible to reduce the environmental impact in the production stage of school buildings. It is difficult to predict the environmental impact of a building as decision-making in the early design phase of the construction project is made under uncertainty. Uncertain factors are included due to various causes in carrying out the building life cycle assessment, and most of the uncertain factors are generated in the process of preparing LCI data. Through this study, it is thought that the simplified life cycle assessment will help make decisions considering environmental characteristics in the early stage of the construction project. Additionally, efficient LCA in terms of time and cost, one of the largest constraints of the existing building LCA, and effective reduction in the environmental load will be possible.

6. Conclusions

This study aimed to analyze the major building materials for streamlining and evaluating the environmental impacts of school buildings as part of the study on the LCA of school buildings. The following conclusions were obtained in the study.

1. As a result of analyzing major building materials in terms of the weight and environment for school building LCA, nine materials (ready-mixed concrete, concrete bricks, aggregate, rebar, cement, stone, glass, insulating materials, and wood) were found to be the major building materials.
2. The weight-based major building materials for school buildings were ready-mixed concrete, concrete bricks, aggregate, rebar, and cement, which represented more than 95% of the total weight.
3. The major building materials from an environmental perspective included ready mixed concrete, concrete bricks, rebar, and cement, which were also weight-based major building materials, as well as insulating materials such as stone, glass, and wood, which are environmentally influential even though they are excluded by the weight-based method.
4. The application of the nine major building materials for school buildings (ready-mixed concrete, concrete bricks, aggregate, rebar, cement, stone, glass, insulating materials, and wood) to school building LCA will contribute toward efficient assessment in terms of time and cost and reduction in environmental load.
5. However, this study needs to be verified through additional data construction because there are not many cases of building life-cycle assessment of school buildings. In the future, it is considered that additional analysis of major building materials according to building characteristics such as purpose and structure of buildings, including school buildings, is necessary.

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